A Study of Cooperation of Multiple Mobile Robots for Object Transportation(複数ロボットによる協調対象物搬送手法に関する研究)

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号	308
発行年	2004
URL	http://hdl.handle.net/10097/13008

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学位の種類	博 士（情報科学）
学位記番号	情 博 第 308 号
学位授与年月日	平成17年3月25日
学位授与の要件	学位規則第4条第1項該当
研究科、専攻	東北大学大学院情報科学研究科（博士課程）システム情報科学専攻
学位論文題目	A Study of Cooperation of Multiple Mobile Robots for Object Transportation（複数ロボットによる協調対象物搬送手法に関する研究）
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論 文 内 容 要 旨

Chapter 1: Introduction

This chapter introduces the topic of object transportation performed by cooperative teams of robots, a subject with several practical applications and exhaustively studied by many research teams but with fewer of them able to show physical implementations that validate theoretical results specially in motion outdoors. This chapter analyzes the salient points of the transportation problem by comparing its two related tasks : First, the widely studied Box Pushing Task and Second, the Carry Task. These task variants are explained with the help of analogies to the way that teams of human beings cooperate to carry load. The chapter evidences how systems oriented to perform the Box Pushing Task have as a common characteristic "intelligence" emerging from interactions between machines with limited manipulation abilities and framed with desirable factors such as robustness, fault tolerance, reliability, flexibility, adaptivity and coherence. The chapter states the thesis main target as to study mechanisms that allow to perform the Carry Task with the simplicity and efficiency characteristic of the Box Pushing Task.

Chapter 2: Related Work

The chapter 2 presents related work on the subject supported by physical experimentation. In a first part, several multirobot instances are introduced following the taxonomic classification introduced by Iocci et al. in which three basic levels are used to locate a given instance: Knowledge, Coordination and Organization. The chapter shows that most of the literature is related to solutions to the problem of cooperative transportation over smooth surfaces. Instances examples related to the carry task are located in the taxonomy as *strong coordinated* since most of the known researches use communication extensively and awared robots. In the second part of the chapter, other instances are introduced by following a classification based in the manipulation method used. These examples show that the carry task usually require sophisticated hardware in constrast with the box pushing task always performed by very simple machines. With the evidence of the examples, the chapter explains that in order to give a solution to the coordinated transportation over moderate rough terrain with multiple robots carring load, it is required a method of cooperation that inherits the simplicity of those strategies designed for the box pushing task.

Chapter 3: Holding without Firm Grasping

This chapter introduces the concept of a prototype of unidimensional controller for a team of robots transporting an object over relative flat terrain under the leader follower schema in which the object is not firmly grasped by any robot. Thus, the object is allowed to slip under the action of inner forces. Combined with friction global balance, each robot, with very reduced capabilities, performs the simple task of relocating on its line of motion at a desired position. The concept is oriented to be used with applications that allow high tolerance since the system can converge to di erent positions at the desired global velocity. The chapter shows that the controller proposed makes the system robust based on redundancy. Thus, in case that one robot find some unexpected problems that can make it unable to cooperate, the task can be performed by the remaining robots. Situations such as low level of charge in batteries, motion over some kind of terrain where slippage appears constantly, or any other hardware inconvenience that can not be recovered by one particular robot are therefore neutralized.

Chapter 4: Definition of the Task

The task performed by the robots is described in this chapter in terms of the related assumptions and constraints. Among the assumptions explained in the chapter: The payload has a uniform distribution of mass, robots reach in steady state symmetrical positions around the object's center of mass, the ground has disperse obstacles no bigger than the radius of one robot's wheel, 75 mm; Robots move on terrain with slopes with small inclination, wheels do not slip on the ground. Motion is quasistatic, consequently the acceleration of robots can be neglected. Constraints correspond to operation with non-holonomic robots that can only act their wheels, with no force or inclination sensing. On the other hand there is no explicit communication between robots, consequently to assess how far the system is from the desired conditions each robot should evaluate exclusively local information.

Chapter 5: Experimental System

Details concerning to the design and construction of the robots used for experimental testing are introduced in this chapter. The system consists of three identical machines, each of which, provides support to the load directly atop the base and employs an arm to track position and report locally any subtle movements of the load. Robots were developed from substantial modifications made to a radio controlled kit (Tamiya TXT-1TM) such as the use of a specifically designed gear box that holds a pair of DC motors with high reduction gear trains for considerable torque and low speed, improvement of the passive suspension system and use of light rigid tires. The payload rests over a cushion that adapts its shape passively and it is contained by a passive rotary box on the top of the robot. A non active arm with 6 degrees of freedom whose extreme is attached by a suction cup to the payload reports its sliding motion over the cushion. This element acts simultaneously as a damper for vibration and it is contained by a passive rotary box on the top of the robot . The machine steers only the frontal wheels.

Chapter 6: Basic Controller

In this chapter the basic ideas introduced in chapter three are presented in detail for the problem of transportation of a long object by the coordinated action of a pair of robots. Focusing on motion performed over relatively flat terrain, experiments verify that if the load slides freely over the top of the robots under the action of inner forces, by controlling the velocity of the robot it is possible to have coordinated motion without explicit communication between robots and with no active actuator different than the robots wheels. This algorithm is aimed to applications that allow some tolerance in the robot's relative position in a teleoperated environment. Since robots can reach the same velocity in asymmetric positions the chapter proposes a mechanism of correction that in such case takes the system to the area in which the controller converges to the target position. A PD controller contributes to adjust the robot relative orientation assuming a top projection. Two different predefined relative target orientations can be assigned to a particular robot depending on its role: Follower: Permanently aligned with the load, Leader: Changes its orientation angle from full alignment, when a translational motion is required, to a predefined orientation when it is necessary to rotate the load and receives a command broadcasted by an operator.

Chapter 7: Active Friction

This chapter extends the concept of using attractive forces between the load and the robot as a mechanism to hold the object. These forces acting through the supporting surface, oppose to the motion of the object and depend on the location of the load relative to the robot. In the simplest situation, when robots move over a surface the attractive force can be reduced to the friction force assumed to satisfy the Coulomb's law of friction. In more challenging situations, such as motion on slopes the attractive force is substituted by magnetic forces whose magnitude is also a function of the relative position emulating natural friction. Several experiments with two and three robots cooperating support the method.

Chapter 8: Summary and Future Work

This chapters summarizes, enumerates the contributions of a distributed cooperation strategy for homogeneous robots with very limited capabilities to transport an object over natural at and sloppy terrain with the simplicity characteristic of the multirobot instances oriented to the box pushing task: No explicit communication between robots. limited sensing capabilities, use of non-holonomic robots, limited number of actuators on-board and simplicity. The simplicity of the mechanical conception of each machine brings robustness and eficiency to the system because it reduces the amount of actuators and sensors on-board. For example, the object is supported by a soft passive cushion that attracts softly the object, emulating friction force, instead of grasping it with a complex manipulator. On the other hand, linking the limitations of each robot to a local simple task makes the control to be fully distributed, avoiding a complex global mathematical model and unnecessary usage of explicit communication, nice characteristics of many instances of multirobot systems designed to perform the box pushing task. Additionally, the attractive forces generated by each robot hold the object but their interaction makes the object to slip over the robots counteracting internal forces in a natural way and making no necessary additional control. The final part of the chapter describes future work.

論文審査の結果の要旨

長大物を複数ロボットの協調作業で運搬する問題はすでにいくつか提案されているが、これらはいずれも平坦走行面上での実現を論じるものであり、また、ロボット間の多量の情報交換を伴うものである。これに対して本論文は、多少の凹凸を含む屋外地をロボット相互間の情報交換をせずに実現する方法について論じたもので、全編７章よりなる。

第１章は序論で、複数ロボットによる協調運搬問題が、協調押し作業問題と異なりもっと広範な作業に適用される協調持ち上げ運搬作業に関して行うことの動機と理由を示している。

第２章では、本研究の主題と関連がある複数ロボット協調運搬問題に関する他の取り組みについてその手法と技術の概要を述べている。そしてこれらのほとんどが多量のロボット間情報交換によってなされていることを述べ、さらにこの中で屋外を想定して行っている唯一の開発例として、NASA が関係する開発プロジェクトを取り上げ、これにおいては精緻なサスペンション制御機構を装備する２台の移動ロボットで実現しようとしているため、情報交換量の膨大さが問題であることを述べている。

第３章では、本研究の手法の特徴の根幹を成す、ロボット間の協調移動の位置速度関係について述べている。すなわち、リーダロボットの移動に運搬対象物を介して追随するフォロワロボットの目標位置・速度ベクトルの導出法の提示と運搬対象物を緩やかに保持することによる対象物移動方向とフォロワロボットの進行方向とのあいだの位置偏差を許容しかつ自らの移動方向ベクトルの算出にこの偏差を利用する手法について述べている。この手法は、着眼と得られる効果に関して顕著な成果である。

第４章では、本論文で取り扱う屋外平地での複数ロボット協調運搬問題についての与条件としての移動環境及び運搬条件について記述している。

第５章では、実験に用いるロボットの機構と構成について述べている。メカニカルサスペンションの効いたロボットの本体機構構成、運搬対象物を固く保持せず固着する方法、運搬対象物とロボットとの位置関係をリアルタイム計測するための計測アームについて詳しく述べている。

第６章では、対象物を２台のロボットで運搬する基本戦略について述べている。さらに提案手法により行った協調運搬実験について述べている。

第７章では、緩い坂でも協調運搬可能とするための方法として用いた「運搬対象物とロボット間での実効摩擦」の概念や緩い坂での協調運搬実験とそのときのデータ、３台ロボットによる協調運搬実験について述べている。

第８章は考察と結論であり、併せて今後の取り組みについても記述している。

以上要するに本論文は、複数ロボットによる協調運搬をロボット間の情報交換をせずに可能とするために、新たな追随法の提案を行い、その有効性を示したものであり、知能ロボット学及び情報科学の発展に寄与するところが少なくない。

よって、本論文は博士（情報科学）の学位論文として合格と認める。